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SYNERGISM OF He-3 ACQUISITION WITH LUNAR BASE EVOLUTION*

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1.0 INTRODUCTION

The 21st century will see great advances in the exploration of space. Beginning with a space station in low Earth orbit and moving toward the settlement of extraterrestrial planets, the exploration and development of space will broaden mankind's horizons. The establishment of a permanently manned Lunar Base would create an excellent stepping stone to future space exploration missions. These advanced missions may support development of large inexpensive power on Earth through the evolution of a very attractive fusion reaction involving deuterium and an isotope of helium, He-3. The advantages of this reaction include: reduced radioactivity due to a reduction of neutrons emitted; improved safety over other fusion reactions and all fission reactions; increased efficiency; and lower electricity costs. Because terrestrial quantities of He-3 would not support a fusion energy economy, researchers are looking to the Moon as a source of He-3 (Wittenberg, 1986). The Moon has been shown to contain approximately 1,000,000 metric tons of He-3 from solar wind bombardment over the past 4 billion years.

This paper will show how acquisition of He-3 affects Lunar Base development and operation. A four-phase evolutionary Lunar Base scenario is summarized with initial equipment mass and resupply requirements. Requirements for various He-3 mining operations are shown and available by-products are identified. Impacts of mining He-3 on Lunar Base development include increases in equipment masses to be delivered to the lunar surface and a reduction of Lunar Base resupply based on availability of He-3 acquisition by-products. The paper concludes that the acquisition of this valuable fusion fuel element greatly enhances the commercial potential of a Lunar Base.

2.0 EVOLUTIONARY LUNAR BASE SCENARIOS

To determine requirements for the establishment of a Lunar Base, various phases of Lunar Base development must be identified. Subsystems required for base operation must be defined. Mass, power, and resupply requirements for these operations must be determined to address overall transportation requirements and cost of operations. From previous Lunar Base concepts and current technology projections, evolutionary Lunar Base scenarios are summarized from previous studies to assess impacts of integrating Lunar He-3 mining into a Lunar Base.

The evolutionary Lunar Base scenarios consist of four phases: (1) a man-tended science base; (2) a manned science and technology base; (3) a manned science and manufacturing base; and (4) a manned science, manufacturing, and export base. Each phase builds on an evolutionary operating capability. The bases's manned capability grows from 4-6 crew members on the man-tended base to supporting 15-20 permanently manned crew members over a period of 23 years.

The initial Lunar Base scenario can support 4 to 6 crew for a 10 day mission. Missions performed on this Lunar Base would be mainly science oriented. Science missions include geology, life sciences/medicine, astronomy, technology testing, and study of energy systems. No provisions for processing lunar regolith for rocket propellant or other resources are provided in this stage of Lunar Base development.

The next stage of Lunar Base development would allow for continuous occupancy of the base by 4 to 6 crew. General science operations would be expanded to include specific studies of geology, life

sciences/medicine, and technology testing. Chemical processing of lunar regolith would involve hydrogen reduction of ilmenite for lunar oxygen. A small scale mining operation would be initiated to supply the base with the needed regolith for lunar oxygen production (6.6 MT lunar regolith per 1 MT lunar oxygen).

In the third stage of Lunar Base development, continuous support for 10 crew is provided. Carbothermal reduction is added to hydrogen reduction to expand regolith processing capability allowing for production of lunar resources beyond lunar oxygen (29.2 MT lunar regolith per 1 MT lunar oxygen + 1 MT lunar silane + 0.4 MT lunar silicon for carbothermal reduction). The additional lunar resources produced can be used for fabrication of structures, solar panels and various other products useful to the base. Provisions to allow manufacturing of these type of products must be provided in this stage of Lunar Base development. Mining operations are expanded to provide the needed additional lunar regolith for manufacturing and production. This expanded mining scenario may include the beginnings of a conveyor network to enable acquisition of larger quantities of lunar regolith.

In the fourth stage of the evolutionary Lunar Base scenarios the base is capable of supporting 15 to 20 crew continuously. To increase the self sufficiency of the base, a process similar to HF acid leach would be added to the chemical processing facility to obtain lunar aluminum and provide the potential to obtain other elemental resources for structures (8.7 MT lunar regolith per 1.0 MT oxygen + 0.6 MT aluminum). Magma electrolysis is added to obtain lunar iron for structures (132.5 MT lunar regolith per 1.0 MT oxygen + 0.8 MT iron). Shiftable conveyors would be added to the mining scenario to provide the additional regolith needed for manufacturing and production. Shiftable and permanent conveyors could be added as the demand for lunar regolith increases.

2.1 Lunar Base Subsystems

Lunar Base subsystems required are determined from the three major operations to be performed by a Lunar Base which include science, manufacturing and production, and infrastructure/support. These operations expand differently as a Lunar Base scenario evolves. Table 2-1 summarizes mass delivery requirements for each subsystem of the evolutionary Lunar Base scenario.

TABLE 2-1. SUBSYSTEM MASS REQUIREMENTS FOR THE EVOLUTIONARY LUNAR BASE SCENARIO

LUNAR BASE SUBSYSTEM	PHASE OF EVOLUTIONARY LUNAR BASE SCENARIO			
	1	2	3	4
SCIENCE	25	125	175	200
MANUFACTURING & PRODUCTION	--	12	431	1115
INFRASTRUCTURE	28	58	133	590

ALL MASSES ARE IN METRIC TONS

Science missions are an important part of any Lunar Base scenario. These missions are needed to provide the information on Lunar geology, life sciences/medicine, astronomy, technology testing, and the study of energy systems. The science system for these Lunar Base scenarios was modeled from the current space station laboratory modules (JSC 30255). In the early stages of Lunar Base development, one module might support small scale experiments for many of these science missions. As the base grows, modules dedicated to a specific types of science missions may be added.

The manufacturing and production system is the main contributor to self-sufficiency capability. While emphasis on this system is low in the early stages of base development, it has the highest priority in an evolved Lunar Base configuration. Manufacturing and production operations include chemical processing for lunar resources, fabrication of hardware or structures from lunar and terrestrial materials, and mining operations for acquisition of lunar regolith. Chemical processing may only involve extraction of oxygen from lunar regolith in the early stages of base development. As the base grows, processing for additional lunar resources will be required. Fabrication of hardware or structures will only be required in fairly evolved Lunar Base scenarios, because larger scale structures and hardware are required before the additional mining and processing operations become cost effective. Mining operations for lunar He-3 include lunar surface transport vehicles, permanent and shiftable conveyors, and beneficiation of lunar ores.

Infrastructure and support includes habitats, launch/landing facilities (includes a mass driver system), maintenance facilities, and power. The infrastructure can be thought of as a base on which all lunar operations are built upon. The infrastructure must provide all resources (mainly consumable, power, thermal, and crew resources) to support science and manufacturing operations. The power plant within the infrastructure can be thought of as LP&L (Lunar Power and Light) and must provide sufficient power for all community needs.

The evolutionary Lunar Base scenarios are capable of utilizing lunar resources after initial operating capability is reached for the second phase of development. Initially, production will be centered on acquisition of lunar oxygen. As the base evolves, structural materials would be needed to ease expansion requirements by using lunar-derived materials. Figure 2-1 shows the production capability of each phase of base development. It is important to note that science system outputs may not be of a product nature, but enhance the knowledge base of Earth and lunar inhabitants.

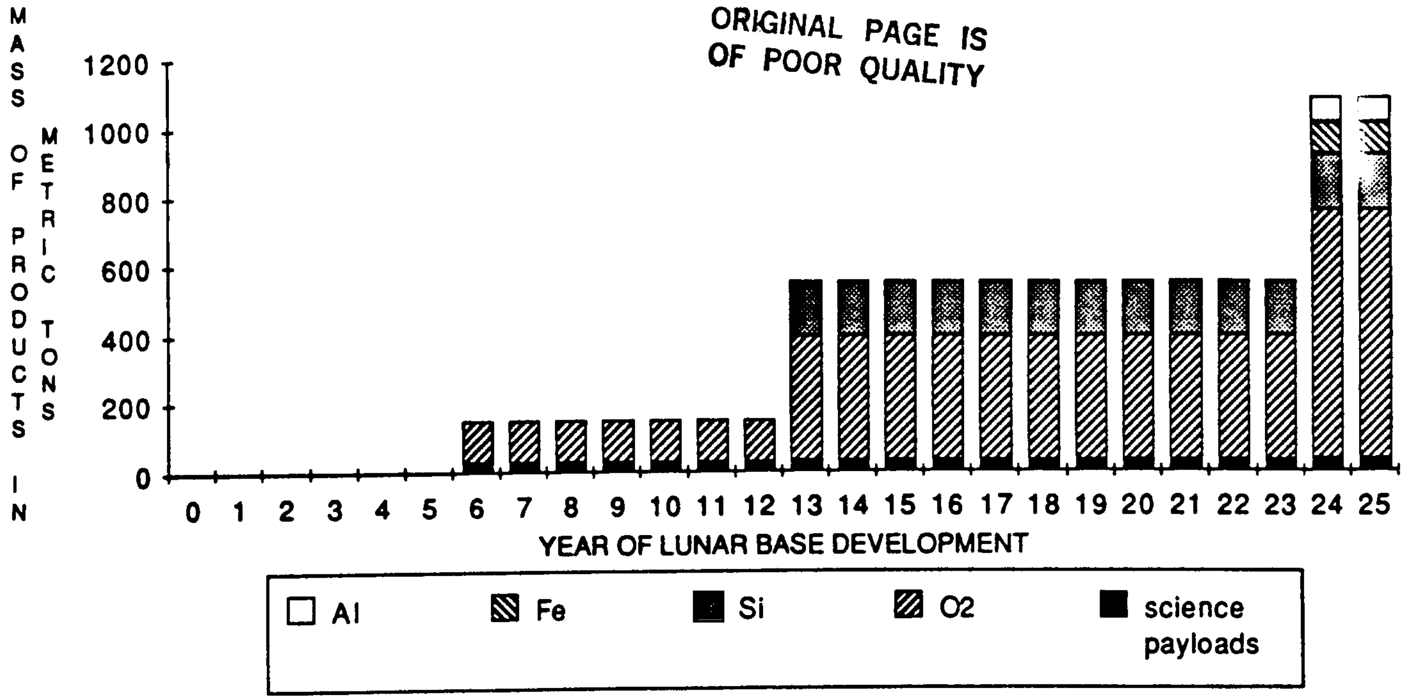

FIGURE 2-1. ANNUAL LUNAR BASE PRODUCTION CAPABILITIES

2.2 LUNAR BASE RESUPPLY

Resupply mass requirements include mass for hardware refurbishment, as well as for consumable replenishment. Resupply requirements have been divided into the three major Lunar Base subsystems. Figure 2-2 summarizes operational resupply requirements for each Lunar Base subsystem and for each phase of base development.

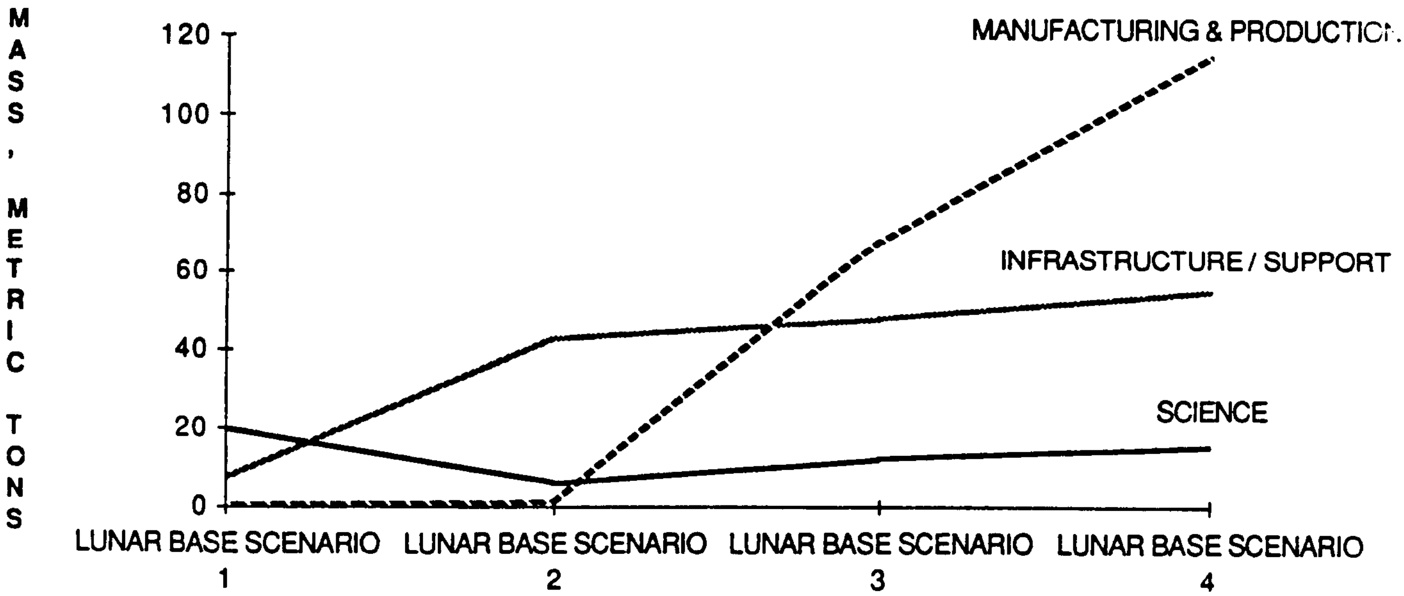

FIGURE 2-2. LUNAR BASE ANNUAL RESUPPLY MASSES

Resupply for the science system is partly comprised of hardware for refurbishment of laboratory modules but is mainly made up of science payloads that are delivered from Earth to conduct scientific experiments on the Lunar surface.

Over 75% of the resupply in the manufacturing and production system is to replenish unrecycled reactants used in processing of Lunar regolith. Some hardware resupply is required to refurbish failed mining system components. Required resupply for unrecycled reactants/consumables and hardware refurbishment is not assumed to be from a Lunar source, although many of the consumables required for regolith processing may be made available from extraction of He-3 and other solar wind gases (will be covered in section 4.1 of this paper).

The major contributor to resupply requirements for the infrastructure\support system originates from life support consumables. Water, the largest consumable in the life support system, may be available in sufficient quantities with the addition of a He-3 mining operation (see section 4.1 of this paper).

A major advantage of He-3 acquisition for a Lunar Base is to make quantities of many consumables that would need to be delivered from Earth available from Lunar resources. To identify these benefits, specific quantities of consumable resources required by a Lunar Base must be identified. Consumable resource requirements can be obtained from analysis of resupply requirements for the manufacturing and production system and the infrastructure\support system. Resupply breakdowns for these Lunar Base systems can be found in Table 2-2.

TABLE 2-2. BREAKDOWN OF CONSUMABLE RESUPPLY

LUNAR BASE SUBSYSTEM	PHASE OF EVOLUTIONARY LUNAR BASE SCENARIO			
	1	2	3	4
PROCESS CONSUMABLES				
H2	--	186	372	558
CH4	--	--	60,000	60,000
HF	--	--	--	33,000
LIFE SUPPORT CONSUMABLES				
H2O	3,350	1,834	3,668	4,280
O2	450	247	493	570
N2	250	137	275	323

ALL MASSES ARE IN kg/yr

These resupply requirements determine transportation requirements for normal Lunar Base operation without expansion considerations. He-3 acquisition may increase hardware mass supply requirements but can relieve the requirement for consumables to be transported to the lunar surface from Earth.

3.0 LUNAR HE-3

Lunar sources of He-3 were first discovered in 1970 by R.O. Pepin (11th Lunar Science Conference). In 1986, a study conducted by scientists at the University of Wisconsin (Wittenberg, 1986) estimated the potential He-3 reserves on the Moon to be one million metric tons. Terrestrial sources of this resource are from the decay of tritium and are estimated at a few hundred kilograms per year. Terrestrial quantities of He-3 are not sufficient for a large scale fusion power industry which would require up to 10 metric tons He-3 per year (Kulcinski, 1988). This section defines requirements of a lunar He-3 mining operation and potential by-products that could be acquired with minimal additional resource requirements.

3.1 Energy Value of He-3

The advantages of fusion energy utilizing He-3 are many. These advantages have been noted by the Fusion Technology Institute and the Nuclear Engineering and Engineering Physics Department of the University of Wisconsin at the Fifth Symposium on Space Nuclear Power Systems (11-14 January 1988). Approximately 600,000 GJ of energy, or 19 $MW_{th}y$, is released upon burning 1 kg of He-3 with deuterium. Thermal to electrical conversion efficiency for the D-He3 fusion reaction is high, approximately 70%. This would yield an electrical energy content of 11.4 MWy per kg of He-3.

Lunar He-3 production levels are estimated to start at approximately 10 kg per year and would increase to several thousands of kg's annually within 30-40 years of the start of lunar He-3 mining. The impacts are very significant on North America energy production and may prove even more significant on future energy requirements in space.

3.2 He-3 Concentrations in Lunar Mare Regolith

Lunar He-3 sources originate from solar winds that have bombarded the lunar surface over the past 4 billion years. Analyses of lunar samples returned in the days of the Apollo missions show helium concentrations in lunar mare regolith of 30 ppm. The concentration of He-3 in helium has been estimated to be 300 ppm. Thus, 1.11 x 10^8 kg of unbeneficiated lunar mare regolith would contain 1 kg of He-3. Since mare samples show a high degree of homogeneity, it is assumed that these concentrations are consistent to at least a 3 m depth. Thus, an area of 25,370 m^2 would contain 1 kg of He-3.

Because the heat capacity of lunar regolith is so low (0.784 J/g K), regolith should be beneficiated as much as possible to reduce the quantities of regolith that must be heated. Beneficiation to remove larger grains can yield reductions of Lunar regolith that must be heated by almost 50% with acquisition of 70-80% of total He-3 available.

3.3 Requirements for He-3 Acquisition

He-3 and other solar wind gas constituents can be removed from lunar regolith through heating. Regolith is collected, beneficiated to a specific grain size fraction, and heated. After heating to approximately 700 C, many of the solar wind gases are evolved. Further processing of these gases would remove He-3 from the solar wind gas mixture. Alternative technologies for the various systems required for lunar He-3 acquisition are included in Figure 3.-1.

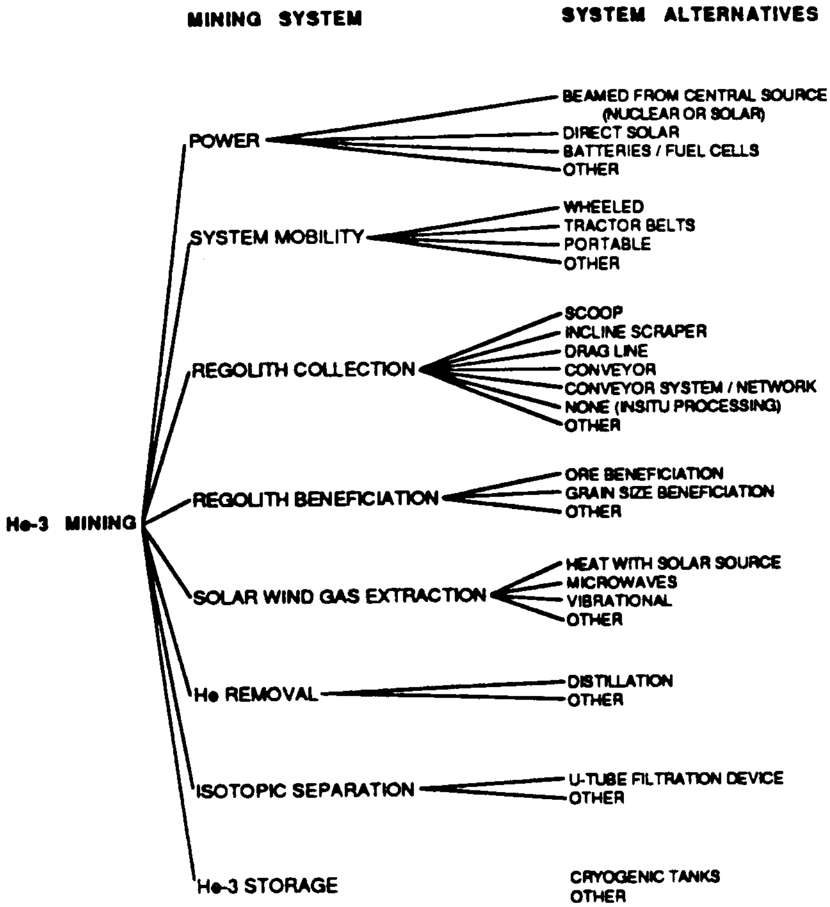

FIGURE 3-1. HE3 MINING SYSTEM ALTERNATIVES

Two scenarios have been conceptualized for the mining of Lunar He-3. The first scenario is a mobile miner that would collect the regolith, beneficiate, and evolve the solar wind gases. The gases would then be collected and stored in gas storage vessels which would be transported to a central facility for further processing. The second scenario is a centralized mining concept where sufficient quantities of bulk lunar regolith would be collected, placed on a conveyor system which would transport the regolith to a central facility for beneficiation, solar wind gas removal, and separation of solar wind gas constituents. A summary of mass and power requirements for each of the He-3 mining scenarios is provided in Tables 3-1 and 3-2 respectively.

TABLE 3-1. MASS SUMMARY FOR HE3 MINING SCENARIOS

ALL MASSES ARE IN METRIC TONS

LUNAR HE-3 MINING CONCEPT	REGOLITH COLLECTION	REGOLITH BENEFICIATION	SOLAR WIND GAS EXTRACTION	SELECTIVE CONDENSATION	ADDITIONAL
MOBILE MINER - 1000 kg He3/yr					
BUCKET WHEEL	152				
INTERNAL REGOLITH TRANSPORT	49				
ELECTROSTATIC BENEFICIATOR		20			
THERMAL POWER FROM DIRECT SOLAR			242		
SELECTIVE CONDENSATION UNIT				180	
GAS STORAGE VESSELS					67
GAS STORAGE VESSEL TRANSPORT VEHICLE					18
MINER MOBILITY SYSTEM & BODY					83
TOTALS	**201**	**20**	**242**	**180**	**168**
CENTRALIZED CONCEPT - 1000 kg He-3/yr					
BUCKET WHEEL EXCAVATORS	200				
CONVEYOR SYSTEM	645				
ELECTROSTATIC BENEFICIATOR		20			
NUCLEAR THERMAL POWER			10		
SELECTIVE CONDENSATION UNIT				180	
TOTALS	**845**	**20**	**10**	**180**	

TOTAL MASS FOR MOBILE MINER = 811 metric tons

TOTAL MASS FOR CENTRALIZED CONCEPT = 1,055 metric tons

TABLE 3-2. POWER SUMMARY FOR HE3 MINING SCENARIOS

ALL POWER VALUES ARE IN KILOWATTS

LUNAR HE-3 MINING CONCEPT	REGOLITH COLLECTION	REGOLITH BENEFICIATION	SOLAR WIND GAS EXTRACTICN	SELECTIVE CONDENSATION	ADDITIONAL
MOBILE MINER - 1000 kg He3/yr					
BUCKET WHEEL	910				
INTERNAL REGOLITH TRANSPORT	152				
ELECTROSTATIC BENEFICIATOR		150			
THERMAL POWER FROM DIRECT SOLAR			4,848		
SELECTIVE CONDENSATION UNIT				5,450	
GAS STORAGE VESSELS					–
GAS STORAGE VESSEL TRANSPORT VEHICLE					242
MINER MOBILITY SYSTEM & BODY					1,110
TOTALS	**1,062**	**150**	**4,848**	**5,450**	**1,352**
CENTRALIZED CONCEPT - 1000 kg He-3/yr					
BUCKET WHEEL EXCAVATORS	870				
CONVEYOR SYSTEM	6,105				
ELECTROSTATIC BENEFICIATOR		150			
NUCLEAR THERMAL POWER			5,675		
SELECTIVE CONDENSATION UNIT				5,450	
TOTALS	**6,975**	**150**	**5,675**	**5,450**	

TOTAL POWER FOR MOBILE MINER = 12,862 kW

TOTAL POWER FOR CENTRALIZED CONCEPT = 18,250 kW

Both He-3 mining scenarios are based on an annual He-3 production rate of 1 metric ton. Thermal energy requirements for solar wind gas evolution are based on the heat capacity of lunar regolith and assume 85% heat recovery. The major difference in the solar wind gas extraction subsystem designs among the alternatives is the source of thermal energy. The mobile miner uses a solar collector/concentrator of smaller thermal output while the centralized system utilizes the high thermal energy output of a nuclear SP-100 reactor. It should be noted that the requirements for the centralized mining concept are impacted by movement of the regolith collection subsystem from a mined area to a different unmined area. Surface preparation requirements for this transportation are not included in either concept. Also, storage requirements for resources obtained following selective condensation are not included in either mining concept.

3.4 Mobile vs. Centralized Mining Concepts

To evaluate and compare each mining concept, advantages and disadvantages of each concept must be identified. The advantages and disadvantages for each mining concept can be found in Tables 3-3 and 3-4.

TABLE 3-3. ADVANTAGES\DISADVANTAGES OF THE MOBILE MINER

ADVANTAGES	DISADVANTAGES
MINIMAL ALTERATION OF LUNAR SURFACE	PREDICTED HE3 DEMANDS WOULD REQUIRE OVER 100 MOBILE MINER SYSTEMS BY THE YEAR 2050
HIGH DEGREE OF AUTOMATION POSSIBLE	OPERATION ONLY DURING THE LUNAR NIGHT REDUCES POTENTIAL HE3 PRODUCTION RATES
NO TEAR DOWN / SET UP REQUIREMENTS FOR MINING DIFFERENT AREAS FAR FROM CENTRAL BASE	BECAUSE MAINTENANCE OF SEVERAL MOBILE MINERS, SOME MANY KM FROM THE CENTRAL BASE, IS VERY RESOURCE INTENSIVE, SYSTEMS WITHIN THE MINER MUST HAVE MINIMAL COMPLEXITY
MULTIPLE MINERS CAN COVER A VERY LARGE SURFACE AREA	
OPERATES FAIRLY INDEPENDENTLY OF OTHER LUNAR BASE OPERATIONS	
HAS A LOWER MASS PER KG HE3 OBTAINED THAN CENTRALIZED CONCEPT	

TABLE 3-4. ADVANTAGES\DISADVANTAGES OF THE CENTRALIZED MINING CONCEPT

ADVANTAGES	DISADVANTAGES
MUCH OF THE HARDWARE REQUIRED COULD BE UTILIZED BY A LUNAR BASE FOR OXYGEN PRODUCTION AND OTHER MINING ACTIVITIES OPERATION DURING THE LUNAR DAY AND NIGHT SINCE MANY OF THE GAS REMOVAL / COLLECTION SYSTEMS ARE CENTRALLY LOCATED, SERVICING / MAINTENANCE IS LESS COSTLY THAN IN MOBILE SYSTEMS AND MAY BE DESIGNED WITH HIGHER LEVELS OF COMPLEXITY USING SOA TECHNOLOGIES	HAS A HIGHER MASS PER KG HE3 THAN MOBILE MOVING THE MINING OPERATION TO ANOTHER LOCATION WOULD BE VERY RESOURCEINTENSIVE BECAUSE MORE SYSTEMS ARE LOCATED IN THE CENTRAL FACILITY THAN WITH THE MOBILE MINER, THERE WILL BE MORE SIGNIFICANT IMPACTS ON THE LUNAR BASE INFRASTRUCTURE SINCE LARGE QUANTITIES OF REGOLITH NEED TO BE DELIVERED TO THE CENTRAL FACILITY FOR PROCESSING, PROBLEMS OF ACCUMULATION OF PROCESSED REGOLITH STOCKPILES MAY ARISE

When studying the advantages and disadvantages of each concept, many tradeoffs become apparent. Because the solar wind gas extraction system in the centralized concept is in one central location, a nuclear reactor could be used to delivered required thermal power enabling gas extraction to occur in the Lunar day and night. Implementing the use of nuclear reactors on the mobile miner would create many maintenance and safety problems because the systems would be more difficult to closely monitor. An advantage of the mobile miner is that large areas may be easily mined at any distance from the central base. As He-3 production requirements increase and as He-3 is removed from regolith nearby the central base, mining operations must extend distances far from the central base. Because movement of excavation systems in the centralized concept would be very costly, the mobile miner has a greater potential to meet long-range He-3 production requirements.

A major advantage of the centralized mining concept over the mobile miner is commonalty of hardware. The excavation and conveyor systems required by the centralized concept can be used to collect regolith for oxygen and other Lunar resource processing schemes. This would reduce the mass delivery requirements for the manufacturing and production Lunar Base system. The excavation systems of the Lunar Base and the centralized He-3 mining concept are identical. The entire conveyor system mass of the fourth phase of the evolutionary Lunar Base scenarios could be provided by the centralized concept also. Considerations of shared hardware reduces mass delivery requirements for the manufacturing and production system by 8% for the centralized He-3 mining concept.

4.0 IMPACTS OF HE-3 ACQUISITION ON LUNAR BASE DEVELOPMENT

To determine the impacts of mining lunar He-3, we must first identify the advantages and disadvantages of each mining concept. We must then consider how the implementation of each mining concept affects the mass delivery requirements of the Lunar Base. The delivery of mining hardware generally increases mass delivery requirements, but the use of by-products made available by such mining would reduce the mass delivery requirements and increase the efficiency of the hydrogen/oxygen Earth-

Moon transportation systems. The value of He-3 and the significant quantities of the by-products available that enhance the commercialization potential of the Lunar Base.

4.1 Available By-products

Many of the other constituents of the solar wind gas mixture are valuable to Lunar Base operations and are obtained with minimal additional resource requirements - thru "synergistic" processing. Table 4-1 lists these available by-products and the quantities available upon heating Lunar regolith to 700 C.

TABLE 4-1. GAS RELEASE PREDICTED FROM HEATING MARE REGOLITH TO 700 C

		CONCENTRATION, ppm (g/metric tonne)				
OPERATION	Regolith (tonnes)	He-3	He-4	H_2	Carbon	Nitrogen
Surface Mining	1	9×10^{-3} 90%	30 90%	50–60 90%	142–226 90%	102–153 90%
Beneficiate $< 50\ \mu m$	0.45	8.1×10^{-3}	27	50	166	115
Heat to 700°C	0.45 (beneficiated)	86% 7×10^{-3}	81% 22	85% 43 (H_2) 23 (H_2O)	3.5% / 2% / 5% 13.5 (CO) 12 (CO_2) 11 (CH_4)	3.2% 4
Per 1 kg He-3	1.37×10^5 (mined) minor gases: neon 0.3 tonnes; argon 0.2 tonnes	1 kg	3.1 tonnes	6.1 tonnes (H_2) 3.3 tonnes (H_2O)	1.9 tonnes (CO) 1.7 tonnes (CO_2) 1.6 tonnes (CH_4)	0.5 tonnes
Per Tonne Regolith into Heater	1 (beneficiated) minor gases: neon 4.8 g; argon 3.2 g	0.016 g	49 g	96 g (H_2) 78 g (H_2O)	30 g (CO) 27 g (CO_2) 24 g (CH_4)	9 g

4.2 Reduction in Lunar Base Logistics

Figure 4-1 shows the overall mass delivery requirement for the evolutionary Lunar Base scenarios without He-3 mining.

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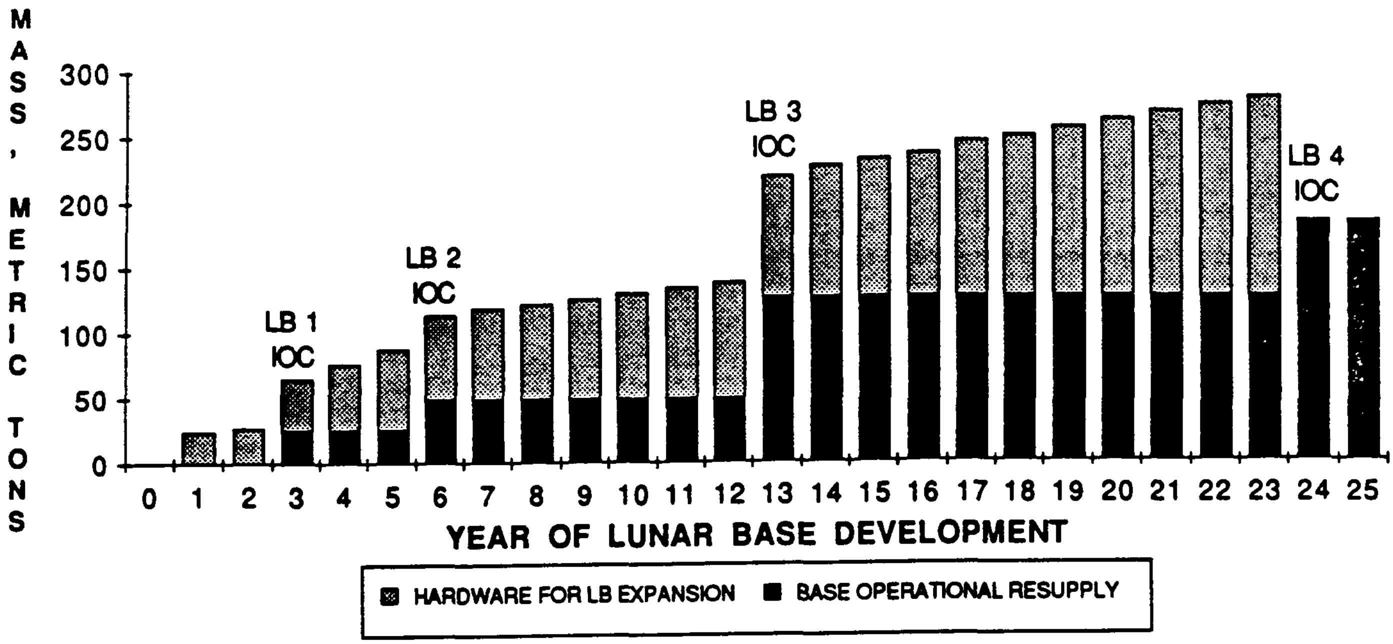

FIGURE 4-1. OVERALL MASS DELIVERY REQUIREMENTS FOR THE EVOLUTIONARY LUNAR BASE SCENARIOS

The impacts of each He-3 mining concept on a Lunar Base can be determined by comparing the mass delivery requirements of the Lunar Base without He-3 mining to a Lunar Base implementing a He-3 acquisition scenario.

Table 2-1 showed resupply requirements for the manufacturing and production system and the infrastructure. The consumables that require resupply may be provided from by-products of He-3 acquisition. Table 4-2 shows the Lunar Base consumable requirements and the quantities available as by-products of He-3 mining scenarios.

TABLE 4-2. ADDITIONAL RESOURCES AVAILABLE FROM HE3 ACQUISITION FOR LUNAR BASE SUPPORT

RESOURCE	APPLICATION TO LUNAR BASE	ESTIMATED REQUIREMENT FOR 15-20 PERSON BASE* (kg/yr)	KG/KG HE3
H2O	LIFE SUPPORT CONSUMABLE	4,280	3,300
O2	LIFE SUPPORT CONSUMABLE	570	2,322[a]
N2	LIFE SUPPORT CONSUMABLE	323	500
H2	LUNAR RESOURCE PROCESS CONSUMABLE	558	6,100
CH4	LUNAR RESOURCE PROCESS CONSUMABLE	60,000	1,600

* LUNAR BASE INCLUDES FULL SCALE MINING OPERATIONS, SCIENCE FACILITIES, SEMI-CLOSED LIFE SUPPORT SYSTEM, AND MMW NUCLEAR POWER SOURCE

It is important to note the quantity of water shown here may be high because a small percentage of the water measured in the early Apollo samples (used to derive this data) may have been influenced by water contamination when returned to and analyzed on Earth. Also, there would be additional requirements to purify the water obtained. Oxygen may be obtained from further processing of CO and CO_2. The effect of supplying Lunar Base consumables from He-3 mining on the overall Lunar Base scenario development can be seen in Figure 4-2. To accurately compare the two He-3 mining scenarios, similar criteria must be applied. Both scenarios have similar He-3 production rates for each year. Both mining concepts assume mass delivery increases of 25% from one year to the next. Both concepts are capable of obtaining 1000 kg of Lunar He-3 per year by the start of the fourth phase of the Lunar Base (year 23).

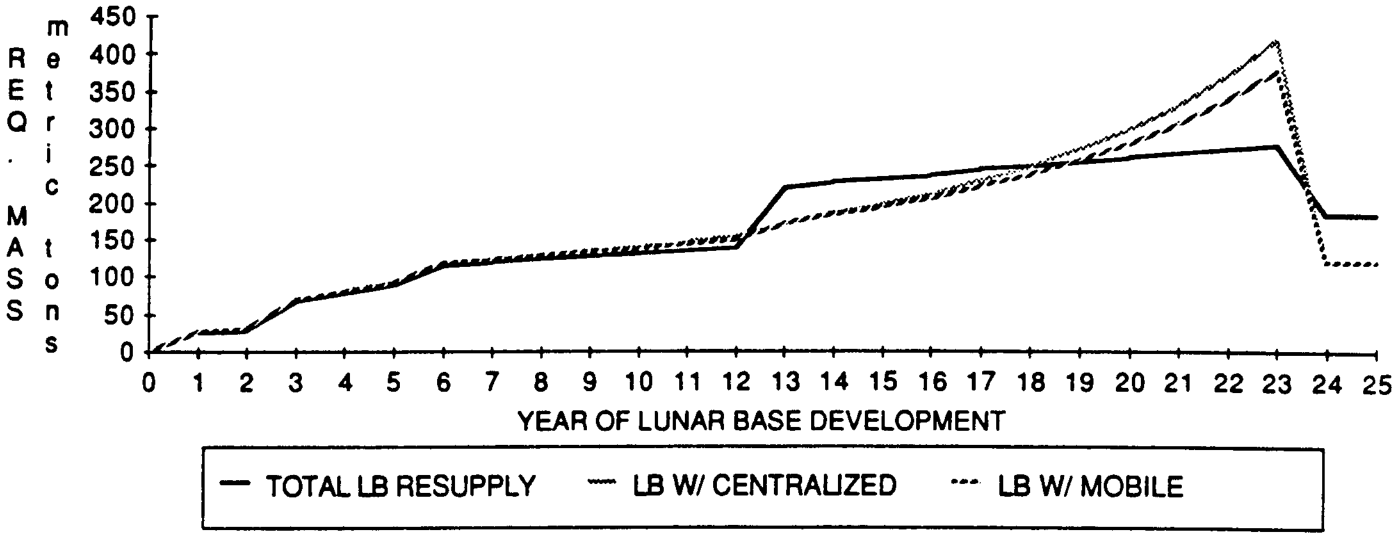

FIGURE 4-2. LUNAR BASE RESUPPLY WITH AND WITHOUT INTEGRATION OF HE3 ACQUISITION SCENARIOS

The mass delivery for a Lunar Base with He-3 mining is actually less than the baseline Lunar Base (without He-3 mining) for He-3 acquisition rates of 100-300 kg/yr and a Lunar Base with 10 permanent crew. This occurs because the He-3 mining operation can resupply the Lunar Base with consumables for life support, atmosphere maintenance, and manufacturing and production processes. In addition to resupplying consumables, the centralized concept delivers all the excavation equipment needed for manufacturing and production operations in the fourth phase of the Lunar Base. The fourth phase is reached by the 23rd year of base development, but hardware delivery for this phase is begun at year 13. After year 23, no expansion of operations is assumed and the Lunar Bases with the He-3 mining operations operate with reduced logistic requirements compared to the baseline case. Also, the effect of He-3 mining will be even greater when a lunar-derived source of both hydrogen and oxygen have been realized in the space transportation system design. The total Earth launch mass per pound of payload to the moon may be reduced by 50% with this source of propellants available (Crabb, Jacobs, Teeter, 1987).

Another measure of the effects of Lunar Base concepts on the space infrastructure is the amount of mass needed to be launched from Earth to deliver all payloads, transport vehicles and other support needs to the Moon. To determine Earth launch mass, the Lunar mass delivery curves (Figure 4-2) are used to

generate an annual mission model. The mission model is then manifested on orbital and launch/landing vehicles that are conceptually defined using ASTROSIZE. ASTROSIZE is a computer model used to design conceptual vehicles from propulsion system characteristics, aerobrakes, landing systems, thrust structures, etc. Total propellant and vehicle requirements are accounted with various sources of propellants considered. The mission model, with space transportation vehicle descriptions (including OTV and lander design), is entered into ASTROFEST. ASTROFEST is a computer code which uses the mission model and vehicle descriptions to determine quantities of Earth propellants, Lunar propellants, and overall Earth launch mass required. Here, the vehicles are sized to account for availability of lunar oxygen and lunar hydrogen if they are available. From these data, the total support of Lunar Base concepts may be evaluated based on the total Earth launch mass including payloads, propellants and vehicles. The results are shown in Figure 4-3.

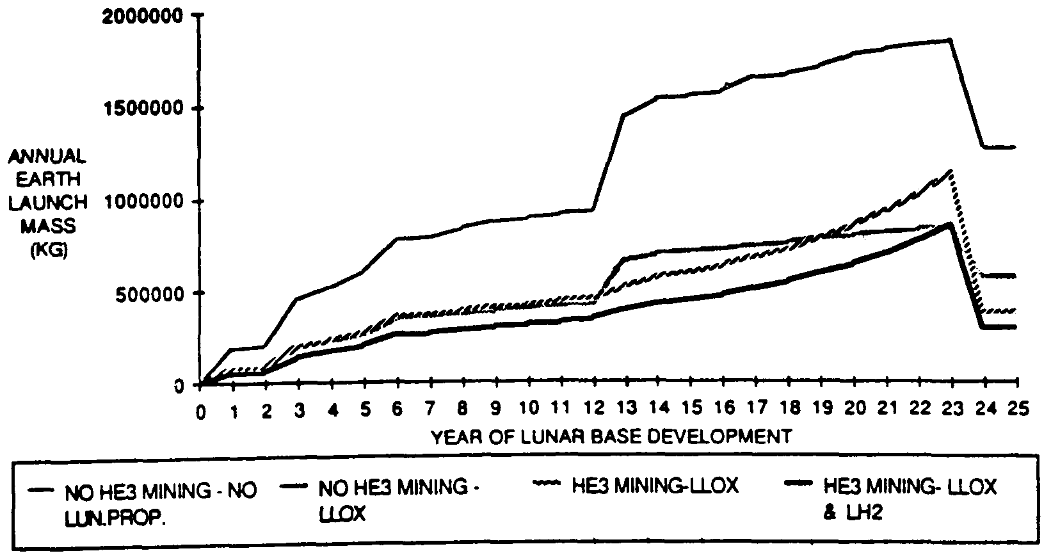

FIGURE 4-3. TOTAL EARTH LAUNCH MASS FOR LUNAR BASE AND LUNAR BASE WITH HE3 ACQUISITION

The results of the Earth launch mass analysis show that He-3 acquisition can reduce the Earth launch burden of establishing a Lunar Base through the provision of consumable gases and propellants. Without He-3 acquisition, O_2 is the most likely propellant candidate from Lunar sources. With He-3 acquisition, H_2 can also be obtained as a by-product and used for propellant. Using H_2 and O_2 from Lunar sources provides enough credits to the Lunar Base with He-3 acquisition to make this scenario less resource intensive than the baseline Lunar Base without He-3 acquisition.

4.3 Increase in Lunar Base Commercialization Potential

In addition to reducing resupply requirements, He-3 acquisition would enhance the commercialization potential of the Lunar Base in several ways. The He-3 could be used provide large quantities of power to a Lunar Base or for the support of other space exploration missions. The by-products could be used by the entire space community. Quantities of He-3 could also be shipped to Earth to support the nuclear energy economy of the 21st Century with the safest known fusion reaction.

4.3.1 Space Markets for He-3 and He-3 Acquisition By-products

As fusion technology advances, many new applications of He-3 will be determined. Researchers are already investigating fusion powered space transportation vehicles. In addition to transportation, quantities of He-3 could provide sufficient power to conduct tasks that would require large amounts of power. A central power plant on the Lunar surface operating on a D-He3 fusion cycle could beam sufficient energy to

run a space station in Low Lunar Orbit. This power plant could also beam energy to other locations on the Lunar surface, thus extending the Lunar Base's range of operation. This energy could also be used to establish and operate other base camps.

A more immediate market that He-3 acquisition opens up for the Lunar Base is the availability of the by-products of He-3 acquisition. By the 10th year of Lunar Base development, excess quantities of He-3 acquisition by-products could be made available for the support of other space activities. These activities include: [1]resupply of the space station with life support and atmosphere maintenance consumables at many times lower cost than delivering from Earth; and [2]Providing needed resources for a Lunar refuel/resupply station for support of other space exploration missions. Figure 4-4 shows the quantities of by-products that could be made available for uses other than the support of a Lunar Base.

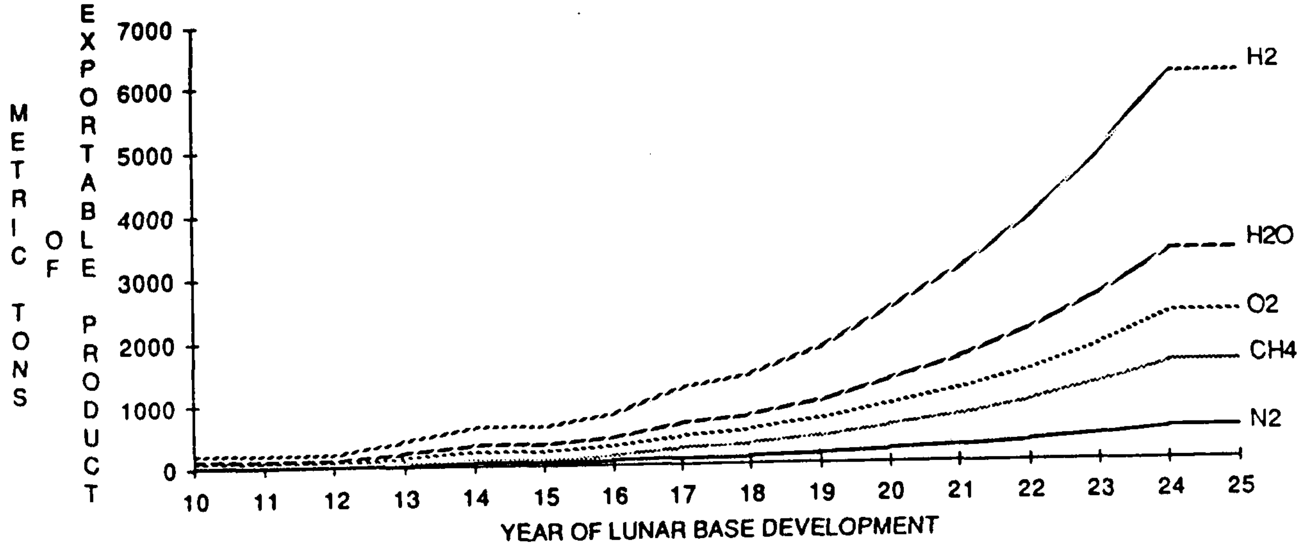

FIGURE 4-4. ANNUAL PRODUCTION OF EXPORTABLE RESOURCES FROM LUNAR HE3 ACQUISITION BY-PRODUCTS

Many other applications of the resources He-3 acquisition makes available may be discovered as manned presence in space grows. The availability of these resources definitely enhances the feasibility of many space exploration missions.

4.3.2 Terrestrial Market for He-3 as a Fusion Fuel

As the 21st Century approaches and fossil fuel supplies diminish, Earth's economy will require much greater amounts of power and energy. Nuclear power does seem to be an answer to the problem but the safety hazards associated with fission reactors has sparked sufficient public concern to hold up development of more nuclear power plants. Nuclear fusion has significantly lower safety risks, and the D-He3 cycle has the lowest safety risk factor of any of the known fusion cycles. Terrestrial quantities of He-3 are not sufficient to support large scale D/He-3 fusion power development, Lunar He-3 is abundant enough to support large scale fusion power on Earth and may provide a strong impetus to return to the moon on a commercial and cost effective basis.

5.0 SUMMARY AND CONCLUSIONS

Here we have shown the value of He-3, a resource scarce on Earth but relatively abundant on the Moon. An evolutionary Lunar Base scenario was presented and impacts of two He-3 acquisition concepts on this base were determined. A centralized He-3 mining concept, where regolith is excavated and returned to a central facility where the He-3 is removed, did have a more significant impact on the Lunar Base than the mobile miner concept, where solar wind gases are extracted from lunar regolith and the gas storage vessels are returned to the central facility for further gas processing. The availability of He-3 acquisition by-products reduced operating requirements of a Lunar Base and provided the base with greater potential for commercialization by making these by-products available for the support of other space missions. Finally, lunar He-3 could support a terrestrial nuclear power economy with the lowest safety risk of any nuclear reaction known. This paper concludes that He-3 acquisition enhances the feasibility of establishing a permanently manned Lunar Base in the early part of the 21st Century.

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